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LABILE TRACE ELEMENTS IN LUNAR METEORITE YAMATO-86032

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Abstract: Contents of siderophile Au, Co and Sb, mobile Ag, Bi, Cd, In, Se, Te, Tl and Zn and lithophile Cs, Ga, Rb and U were determined by RNAA in samples of the lunar meteorite (anorthositic breccia) Yamato (Y)-86032. Contents of the 4 lithophiles in matrix (,75AM) and anorthositic clast (,101AC) are similar to those in samples of the other 3 lunar meteorites. This is consistent with all these anorthositic breccias being from the lunar highlands. Contents of the other 11 elements indicate a micrometeorite component of 2.5±1.1% (Cl-equivalent) in the parent regolith of Y-86032,75AM. This value is unusual for lunar samples and is virtually identical to the value for the paired samples Y-82192/3 found in the same bare ice region, suggesting that these 3 specimens derive from the same lunar region in the same impact. No micrometeorite component is detectable in Y-86032,101AC. Slight compositional differences between Y-82192/3 and Y-86032 indicate that they did not travel Earthward as a single rock. Allan Hills-81005 and Y-791197 each exhibit characteristic siderophile/mobile element patterns indicating deviation from different parent regions in separate events. Hence, the 5 lunar meteorites studied thus far derive from 3 distinct impacts.

1. Introduction

The Antarctic ice sheet has proven to be a unique source for lunar meteorites and, indeed, our only source of new lunar samples for the past 2 decades. These meteorites were launched Earthward by impacts on the Moon sufficiently intense to eject them with velocities ≥2.4 km/s, lunar escape velocity. From the undisturbed nature of thermally-sensitive indicators in lunar meteorites (labile trace elements, tracks), shocks associated with this velocity-impulse were not unusually intense, *i.e.* were comparable with those experienced by C or H chondrites and less severe than those that produced even moderately shock-loaded, 20–35 GPa, L chondrites (VERKOUTEREN *et al.*, 1983; LINGNER *et al.*, 1987).

Labile (*i.e.* volatile and/or mobile) trace elements not only give information on meteorite shock exposure but, because of their ready loss in response to extended heating, they yield unique genetic information important in characterizing meteorite thermal histories. In the case of lunar meteorites, for example, differences in their patterns of trace element contents convincingly argue for derivation of Allan Hills (ALHA)-81005, Yamato (Y)-791197 and Y-82192/3 (the paired samples Y-82192 and Y-82193) from 3 different lunar regions, each in a separate massive impact

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(VERKOUTEREN *et al.*, 1983; KACZARAL *et al.*, 1986; DENNISON *et al.*, 1987). Other data (chemical, petrologic, noble gas, *etc.*) are consistent with this view (*cf.* WARREN *et al.*, 1989). Furthermore, ALHA-81005 was found on the other side of the Antarctic continent from the Yamato samples and Y-791197 differs markedly from Y-82192/3 in appearance in the hand specimens: curiously, all of these meteorites are anorthositic breccias. In particular, Y-82192/3 shows evidence for a short melting episode on the Moon, that affected only a portion of the meteorite. Contents of mobile trace elements indicate small but real loss from the melted portion of Y-82192 compared with the "normal" part of it (DENNISON *et al.*, 1987).

The discovery of Y-86032, a relatively large (650 g) anorthositic breccia—10× more massive than any other such sample—presented us with yet another piece in the lunar meteorite puzzle. In physical appearance, it resembles Y-82192/3 and was found in the same bare ice area where they were found (TAKEDA *et al.*, 1989). This raised the supposition that Y-86032 was paired with Y-82192/3, an assumption that had to be checked. We were invited to join the Consortium constituted to investigate this question and were delighted to be included. Here, we report our data for Ag, Au, Bi, Cd, Co, Cs, Ga, In, Rb, Sb, Se, Te, Tl, U and Zn in Y-86032, elements that we also had determined in the other lunar meteorites.

2. Experimental

To minimize sample consumption and heterogeneity problems, we analyzed by RNAA a sample of matrix (,75AM) and clast (,101AC) after INAA study by LINDSTROM *et al.* (1990). Conservation of material, while always important, is not critical for the 650 g Y-86032: it is critical for Y-793274, an 8.66 g lunar meteorite yet to be studied by the consortium. Our study of Y-86032 in this manner would then serve as a feasibility test for joint RNAA-INAA measurements of the same material from Y-793274, the smallest lunar meteorite yet found.

Petrologic descriptions of the samples of Y-86032 that we studied—matrix ,75AM (128.6 mg) and anorthositic clast ,101AC (37.4 mg)—were given by LINDSTROM *et al.* (1990). During INAA, these samples had been irradiated for 20 h at 4.9×10^{13} n/cm^2/s. The neutron fluence in our 10-day RNAA irradiation at 8×10^{13} n/cm^2/s in the University of Missouri Research Reactor was so much greater than in the INAA irradiation, that we could ignore activities produced in the earlier run. This was confirmed by comparing count rates for our monitors included in the INAA run with those included in the RNAA run.

Monitor preparation, chemical processing, counting procedures and data-reduction techniques are as described by PAUL (1988). Chemical yields were satisfactory, ranging up to 92%, and exceeded 25% for all samples but Ag in ,75AM (23%) and Sb in ,101AC (14%). Chemical yields for monitors exceeded 50% in all cases and ranged up to 95%. As is usual in our group, replicate portions of Allende Meteorite Reference Sample had previously been analyzed to assure the quality of our data.

Table 1. Trace element data for lunar meteorites Yamato-86032 and 82192/3.

Element*	Y-86032				Y-86032		Y-82192		Y-82192/3	
	,101AC	,75AM	,101AC[1]	,75AM[1]	Range[2]	Mean§	,83C[3]	,52C1[3]	Range[2]	Mean§
Siderophile										
Co (ppm)	8.2	9.3	11.6	14.6	13.1–14.9	14.4 (6)	8.4	14.8	16.0–19.9	18.1 (5)
Au	0.79	1.86	<1.0	3.0±0.4	1.3–6	2.4 (5)	1.2	12.1	1.1–3.1	1.7 (4)
Sb	1.8	4.3			<50	<15 (2)	2.8	4.2		<100 (2)
Mobile										
Se	302	283	300±60	470±60	300–400	400 (2)	504	338	<200–300	300 (1)
Te	6.5±0.7	29.3					≤2.8	22.3		
Bi	0.68±0.05	2.99					4.5	3.9		
In	1.8	3.0					0.38±0.21	2.6±0.2		
Ag	1.2	5.6			<80	<80 (1)	2.7±0.3	3.7		
Zn (ppm)	3.33	5.32			6.4–14	9.1 (3)	1.30	4.63	6.7–30	15 (3)
Tl	5.2	4.8					3.2	3.0		
Cd	29.2	31.7					4.6±0.8	20.2	7.9–40±13	25 (2)
Lithophile										
Rb	241	248			<10000	<1000 (2)	61.8	230	≤3000	≤3000 (2)
Cs	15.5	10.5	31±10	58±9	50–<140	50 (4)	4.8	19.9	80–<160	80 (3)
Ga (ppm)	2.94	3.89			3.4–4.8	3.66 (3)	3.18	2.86	2.8–10.4	5.8 (3)
U	46.0	59.1	<49	46±12	32–70	51 (5)	7.0	50.6	40–66	54 (4)

[1] LINDSTROM *et al.* (1990); [2] Ranges of data for bulk samples by all authors cited in KOEBERL *et al.* (1989) and WARREN *et al.* (1989); [3] DENNISON *et al.* (1987).

§ Means for Y-86032 are weighted averages given by KOEBERL *et al.* (1989); means for Y-82192/3 are averages that we calculated from data by other authors cited in KOEBERL *et al.* (1989). For both, the number of values used in calculating means is given in parentheses.

* Concentrations are in ppb unless otherwise noted.

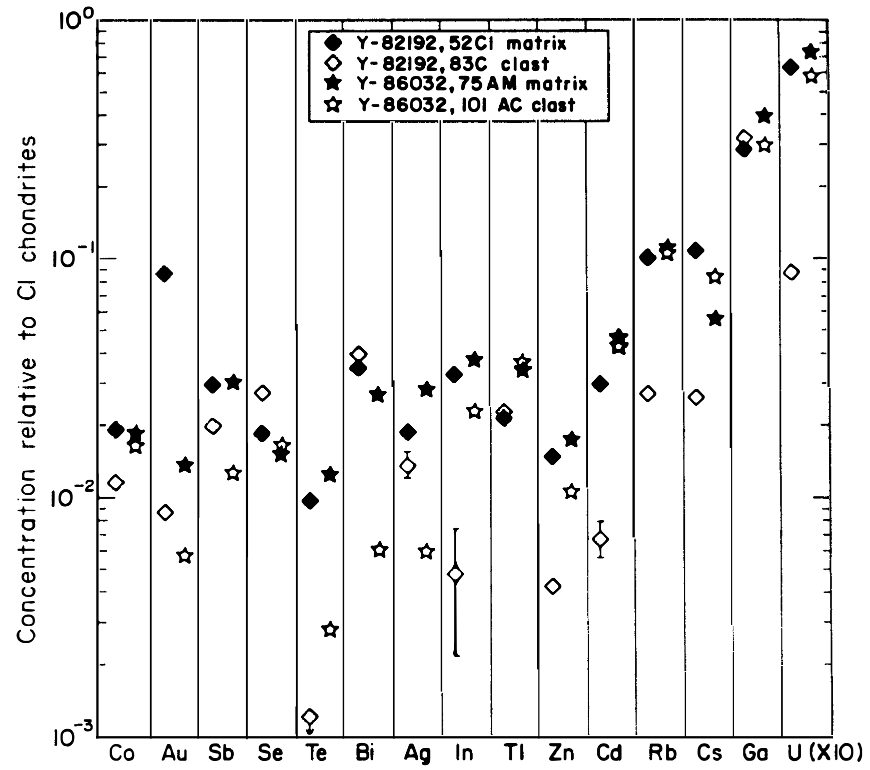

Fig. 1. C1-normalized contents of 3 siderophile (Co→Sb), 8 mobile (Se→Cd) and 4 lithophile (Rb→U) trace elements in the matrix of and in an anorthosite clast in Y-86032. Data for analogous samples from Y-82192 are shown for comparison (DENNISON et al., 1987). Lithophiles are at the high levels common to lunar anorthositic breccias. The other 11 elements in Y-86032,75AM indicate the presence of 2.5±1.1% (C1-equivalent) of micrometeorite component compared with 2.4±0.8% (C1-equivalent) introduced into the parent regolith of Y-82192,52C1. Both specimens were ejected from the same parent region in the same impact: differences for Au and other more refractory elements suggest that Y-82192/3 and Y-86032 were not part of the same rock. Allan Hills-81005 and Y-791197 were each produced by separate impacts in yet other lunar regions (see text).

3. Results

We list our results for Y-86032 in Table 1 and depict these concentrations, normalized to those in C1 chondrites (ANDERS and GREVESSE, 1989), in Fig. 1. Where comparison of our results and others' is possible—either for the specific samples ,75AM or ,101AC (by INAA) or for bulk splits of Y-86032 (and Y-82192/3)—we list the data in Table 1. Table 1 and Fig. 1 also include results of DENNISON *et al.* (1987) for analogous samples of Y-82192: anorthositic clast ,83C and unmelted matrix ,52C1.

Our biggest concern is with the Co data. Our RNAA results for ,101AC and ,75AM are 29% and 36%, respectively, lower than INAA measurements (LINDSTROM *et al.*, 1990) for exactly the same samples. The difference is a systematic one: our Co value for Y-86032,75AM is 35% lower than the weighted mean for bulk samples of this meteorite and the datum for Y-82192,52C1 from our group (DENNISON *et al.*, 1987) is 18% lower than the mean value for this meteorite (Table 1). Bholghati samples show similar systematic differences (WANG *et al.*, 1990). These differences seem

Table 2. Trace element concentrations in Allende (C3V) Meteorite Reference Sample.

	This work*	Purdue mean†
Ag (ppb)	102±4 (5)	99.0±9.5 (59)
Au (ppb)	146±5 (6)	145±9 (27)
Bi (ppb)	49.0±1.5 (6)	48.6±3.4 (4)
Cd (ppb)	494±11 (14)	505±56 (56)
Co (ppm)	619±19 (11)	614±39 (66)
Cs (ppb)	87.3±3.0 (14)	86.9±5.3 (60)
Ga (ppm)	6.00±0.19 (11)	6.21±0.55 (47)
In (ppb)	28.7±1.2 (9)	30.3±3.4 (52)
Rb (ppm)	1.08±0.04 (15)	1.11±0.13 (54)
Sb (ppb)	84.6±4.5 (6)	84±14 (38)
Se (ppm)	8.88±0.17 (11)	8.74±1.09 (44)
Te (ppm)	0.980±0.049 (13)	1.02±0.09 (65)
Tl (ppb)	60.7±3.3 (10)	61.0±4.7 (68)
Zn (ppm)	117±6 (15)	116±7 (65)

* Split 22, position 25. Mean value and one sample standard deviation are listed for the number of replicates analyzed (in parentheses).

† Mean value and one sample standard deviation are listed for the number of replicates shown in parentheses (DENNISON *et al.*, 1986; LINGNER *et al.*, 1987 and references listed therein; KACZARAL *et al.*, 1989).

to be evident only at low Co concentrations since they are not observed for Allende Meteorite Reference Sample. Our Co data, indeed all of our results for Allende Meteorite Reference Sample, are in excellent agreement with prior results from our group (Table 2). As discussed by LINGNER *et al.* (1987), mean values from our group for Allende Meteorite Reference Sample do not differ significantly from all other (and much fewer) data for it. Apart from noting the Co discrepancy, we cannot determine the reason for it.

For other elements determined both by RNAA and INAA in Y-86032,101AC and ,75AM, discrepancies seem due to the INAA values (Table 1) which either are near their detection limits, may not be properly corrected for interferences and/or may reflect inhomogeneous standards (D. W. MITTLEFEHLDT, pers. commun.). These facts, together with the internal consistency of our data, cause us to accept our results without further question.

4. Discussion

The trace element pattern exhibited by the Y-86032 samples that we analyzed is very straightforward. For practically every element, contents in the anorthositic clast ,101AC are at or below those in the matrix ,75AM. Only for Cs is this reversed and even here the difference is not at the factor-of-two level taken to signify a major difference (Table 1, Fig. 1). Contents of Cl-normalized siderophile and mobile trace elements are well below those of lithophiles, a trend typical of lunar highlands samples (Fig. 1). In such materials, Ga typically seems to behave as a lithophile (VERKOUTEREN *et al.*, 1983; KACZARAL *et al.*, 1986; DENNISON *et al.*, 1987), as in basaltic achondrites (*e.g.*, PAUL, 1988; WANG *et al.*, 1990), rather than as a siderophile or mobile element, as in chondrites. This behavior is manifested by its relatively constant and high contents in lunar meteorites, generally ranging from 0.25–0.39×Cl (VERKOUTEREN *et al.*, 1983; KACZARAL *et al.*, 1986; DENNISON *et al.*, 1987; Fig. 1). These levels are more typical of lithophiles like Rb and Cs than of non-lithophiles and we have chosen to group Ga with Rb, Cs and U than with other elements in Fig. 1.

Cl-normalized contents of 11 elements (siderophilic Co, Au and Sb and mobile Se, Te, Bi, Ag, In, Tl, Zn and Cd) are rather constant in Y-86032,75AM at 0.025±0.011×Cl. We interpret this as indicating micrometeorite admixture to the tune of 2.5±1.1% (Cl-equivalent) to Y-86032,75AM parent regolithic material. Several siderophiles usually serve as markers for admixed projectile into ejecta from crater-forming impact events: only Au of those elements is included in our trace element suite, the others being much more refractory. We consider it significant that Au in Y-86032 ,75AM is at the same Cl-normalized level as all other siderophiles and mobile trace elements, indicating the absence of projectile contribution to Y-86032 (Fig. 1). In this respect, Y-86032 resembles ALHA-81005 and differs from Y-791197 and Y-82192/3.

The pattern for matrix Y-86032,75AM may be contrasted with that of Y-82192 ,52Cl—an analogous sample (DENNISON *et al.*, 1987). As can be seen from Table 1 or Fig. 1, the latter sample contains considerably more Au than the former. KOEBERL *et al.* (1989) also report generally lower values for refractory siderophiles (including Au) in Y-86032 than in Y-82192, reflecting proportionately less meteorite debris from the projectile. They note, however, that the variability of those siderophiles in Y-86032 "may be due to incorporation of various amounts of meteoritic debris" in different samples. Other elements in Y-82192,52Cl are at levels comparable with, but very slightly lower than, levels in Y-86032,75AM. For 10 siderophile and mobile trace elements (Au omitted), DENNISON *et al.* (1987) report 2.4±0.8% micrometeorite (Cl-equivalent) admixture in Y-82192: for the same 10 elements, the micrometeorite contribution in Y-86032 is 2.6±1.1%.

Other than to note that trace element contents in (igneous) anorthositic clasts from Y-86032 and Y-82192 are generally lower than those in the corresponding matrix samples (Table 1, Fig. 1), little can be added. Data for siderophile and mobile trace elements in each scatter badly, indicating the absence of significant micrometeorite component. Is it significant that contents of highly mobile In, Tl, Zn and Cd and lithophile Rb, Cs and U are higher in Y-86032,101AC than in Y-82192,83C? We do not know.

The major unanswered question at this point is the uniqueness of Y-86032 relative

Table 3. Admixed components in lunar meteorites from contents of labile trace elements.

	Admixture, Cl-equivalents (Ref.)
ALHA-81005	Meteoritic, 1.3±0.5%* (VERKOUTEREN *et al.*, 1983)
Y-791197	Volcanic emanation condensate (KACZARAL *et al.*, 1986)
Y-82192	Meteoritic, 2.4±0.8%* (DENNISON *et al.*, 1987)
Y-86032	Meteoritic, 2.5±1.1%* (This work)

* Elements used: Ag, Bi, Cd, Co, In, Sb, Se, Te, Tl and Zn for all samples but Y-86032 which also included Au.

to other lunar meteorites studied thus far. Prior data for our suite of trace elements indicate the unique nature of each lunar meteorite (Table 3). Results from Y-86032 matrix clearly distinguish it from ALHA-81005 and Y-791197 but not Y-82192/3. The proportions of micrometeorite component in Y-82192/3 and Y-86032 are unusually high for lunar samples: these typically are <2% (Dennison *et al.*, 1987). This alone suggests that Y-82192/3 and Y-86032 derive from the same general region of the Moon, but differences in contents of Au (Table 1) and other refractory elements (Koeberl *et al.*, 1989; Warren *et al.*, 1989) suggest that the region was chemically heterogeneous. The chemical differences between Y-82192/3 and Y-86032 suggest that they were not part of the same nugget in space but may well have been launched Earthward from the same general lunar region in the same impact. Only measurements of cosmogenic stable and radionuclide contents can settle this question, however.

5. Conclusion

Contents of lithophile Cs, Ga, Rb and U in Y-86032 matrix (,75AM) and anorthositic clast (,101AC) are high and similar to those of samples from other lunar meteorites—ALHA-81005, Y-791197 and Y-82192/3—consistent with all being anorthositic breccias from the lunar highlands. C1-normalized contents of siderophiles (Au, Co, Sb) and mobile trace elements (Ag. Bi, Cd, In, Se, Te, Tl, Zn) are at similar levels suggesting micrometeorite admixture of 2.5±1.1% (C1-equivalent) to the regolith from which Y-86032,75AM formed. Trace element contents of anorthositic clast Y-86032,101AC are lower than those in ,75AM (Ag, Au, Bi, In, Sb, Te, Zn) or equivalent to them for other elements. Trace element contents in Y-86032,101AC generally scatter as do those in its analogue, Y-82192,83C and the two anorthositic clasts differ compositionally from each other.

The similarity in the C1-normalized Au content of Y-86932,75AM to levels of 10 other siderophiles and mobile trace elements in it suggests that the signature of the impacting projectile that sent Y-86032 Earthward is absent. (Refractory siderophile heterogeneity may be a problem in this connection.) In this respect, Y-86032 is like ALHA-81005 but unlike other lunar meteorites. Trace element contents in Y-86032 ,75AM are very similar to those of Y-82192/3 and differ from those of other lunar meteorites. In particular, the high degree of siderophile and mobile trace element (micrometeorite-derived) enrichment in Y-86032 is very similar to that in Y-82192/3 (2.4±0.8% C1-equivalent). These differ significantly from the analogous value for ALHA-81005, 1.3±0.5% (C1-equivalent), which is more normal for lunar anorthositic breccias, and from the generally volatile-rich pattern for Y-791197, which apparently contains condensed emanations from lunar volcanism.

Yamato-86032 apparently derives from the same lunar region that produced Y-82192/3 and all 3 samples were probably sent Earthward by the same major impact. The small but real chemical differences between Y-86032 and Y-82192/3 suggest that they were not part of the same rock launched from the Moon at or above its escape velocity, >2.4 km/s. ALHA-81005 and Y-791197, on the other hand, apparently derive from two other lunar highland regions in separate major impacts. We eagerly await Y-793274 to see if the Antarctic ice sheet has sampled more than the 3 separate impacts on the Moon represented by the 5 lunar meteorites studied thus far.

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